

Final Report Submitted to the  
Air Force Office of Scientific Research  
for research on

**Manipulating Local Electronic Properties of Carbon Nanotubes**  
**Agreement # FA9550-05-1-0353**

Principal Investigator:  
D. Goldhaber-Gordon

Geballe Laboratory for Advanced Materials  
McCullough Building Room 346  
476 Lomita Mall  
Stanford University  
Stanford, CA 94305

May, 2008 (actually submitted July, 2008)

<b>REPORT DOCUMENTATION PAGE</b>				<i>Form Approved</i> OMB No. 0704-0188	
<small>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</small>					
<b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</b>					
1. REPORT DATE (DD-MM-YYYY) 07/16/08		2. REPORT TYPE FINAL PERFORMANCE REPORT		3. DATES COVERED (From - To) 05/01/05 - 02/29/08	
4. TITLE AND SUBTITLE Manipulating Local Electronic Properties of Carbon Nanotubes				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER FA 9550-05-1-0353	
				5c. PROGRAM ELEMENT NUMBER	
				5d. PROJECT NUMBER	
6. AUTHOR(S) GOLDHABER-GORDON, DAVID				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) STANFORD UNIVERSITY OFFICE OF SPONSORED RESEARCH 320 PANAMA ST., STANFORD, CA 94305-4100				8. PERFORMING ORGANIZATION REPORT NUMBER  SPO # 33808	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AF OFFICE OF SCIENTIFIC RESEARCH 875 NORTH RANDOLPH STREET ROOM 3112 ARLINGTON VA 22203				10. SPONSOR/MONITOR'S ACRONYM(S)  AFOSR	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT UNLIMITED					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT  Carbon nanotubes have many emerging technological uses, from strengthening lightweight composite materials to reducing voltage requirements in field-emission displays. Companies such as IBM and Intel have substantial research efforts aimed at the more complex task of building transistors and computer processors from nanotubes. Research under this proposal addresses one of the important requirements for achieving that vision: understanding and modifying electron flow in one-dimensional systems (carbon nanotubes) by local gating, to create transistors. We have succeeded in making transistors on nanotubes using narrow top-gates, and have also developed a method to dynamically measure local heating in nanowires.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Laraine Lietz-Lucas
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 650-736-2045

## INSTRUCTIONS FOR COMPLETING SF 298

**1. REPORT DATE.** Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

**2. REPORT TYPE.** State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

**3. DATES COVERED.** Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

**4. TITLE.** Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

**5a. CONTRACT NUMBER.** Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

**5b. GRANT NUMBER.** Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

**5c. PROGRAM ELEMENT NUMBER.** Enter all program element numbers as they appear in the report, e.g. 61101A.

**5d. PROJECT NUMBER.** Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

**5e. TASK NUMBER.** Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

**5f. WORK UNIT NUMBER.** Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

**6. AUTHOR(S).** Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES).** Self-explanatory.

**8. PERFORMING ORGANIZATION REPORT NUMBER.** Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES).** Enter the name and address of the organization(s) financially responsible for and monitoring the work.

**10. SPONSOR/MONITOR'S ACRONYM(S).** Enter, if available, e.g. BRL, ARDEC, NADC.

**11. SPONSOR/MONITOR'S REPORT NUMBER(S).** Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

**12. DISTRIBUTION/AVAILABILITY STATEMENT.** Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

**13. SUPPLEMENTARY NOTES.** Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

**14. ABSTRACT.** A brief (approximately 200 words) factual summary of the most significant information.

**15. SUBJECT TERMS.** Key words or phrases identifying major concepts in the report.

**16. SECURITY CLASSIFICATION.** Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

**17. LIMITATION OF ABSTRACT.** This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

**Objectives:**

Carbon nanotubes have many emerging technological uses, from strengthening lightweight composite materials to reducing voltage requirements in field-emission displays. Companies such as IBM and Intel have substantial research efforts aimed at the more complex task of building transistors and computer processors from nanotubes. Research under this proposal addresses one of the important requirements for achieving that vision: understanding and modifying electron flow in one-dimensional systems (carbon nanotubes) by local gating, to create transistors.

**Status of effort:**

As of the end of funding, Feb 29, 2008, funding had been going for nearly three years on this project. The nominal start date was April 1, 2005, but the issue date by the AFOSR was June 10, 2005, and funding was activated at Stanford on July 1, 2005.

**Accomplishments:**

1. Locally-gated nanotube devices have been fabricated 100 or more at a time, in a manner that may lead the way to scalable devices. After growth of nanotubes at an array of locations, contacts and gates are deposited without a time-consuming and laborious search for nanotubes. Our yield of working devices is roughly 30%. We expect this could be enhanced dramatically by using tailored catalyst (iron nanoparticles) and any of several established techniques for aligning nanotubes during growth (e.g. electric field, gas flow.)
2. The silicon substrates we (and many of our colleagues) were using as large-area gates for nanotubes were shown to contribute to hysteresis in electrical measurements at low temperature due to insufficient doping. Also, oxides grown by the wafer vendors had very low breakdown voltage. We obtained more heavily doped substrates (5 milliohm cm) and learned to grow our own high-quality oxides at the Stanford Nanofabrication Facility. This has benefited projects on both my AFOSR grants, as well as early work on the newly-exciting material graphene (a single sheet of graphite.)
3. Processes for locally gating nanotubes have been transferred from facilities at Hitachi Global Storage Technologies (where AFOSR-supported graduate student Joseph Sulpizio developed these processes together with Hitachi scientist Zvonimir Bandic.) This was necessary because fab facilities at Hitachi were taken down for months when they moved their lab, and those facilities are now less accessible for us. Steps we've taken include:
  - a. Purchasing and installing a used scanning electron microscope (SEM) together with two Stanford Material Science research groups.
  - b. Setting up e-beam lithography capability on this SEM, and achieving 30 nanometer features with 100 nanometer alignment, plus making large arrays over a 4" wafer in an automated manner. These are the requirements for the devices we're making.
  - c. Developing etching and metal deposition processes in the Goldhaber-Gordon lab and at the Stanford Nanofabrication Facility.

Joseph Sulpizio has been directly responsible for all of these developments.

4. A new cryostat was set up for measurement of the nanotube devices, and has been tested by measurement of low-disorder suspended nanotube devices in collaboration with the lab of Hongjie Dai (the major pioneer of our CVD method of nanotube growth.) Charis Quay has been primarily responsible for these steps.

5. Successful top-gating of graphene, a novel material consisting of a single layer of carbon atoms

### **Personnel supported or associated with work:**

Principal Investigator:

David Goldhaber-Gordon, Assistant Professor of Physics

Graduate students (external fellowships supplemented):

Charis Quay, Ph.D. student in Physics: working on nanotube transistors and nanotube variants: “peapods”. Graduated Dec. 2007.

Joseph Sulpizio, 5<sup>th</sup> year in Physics: working on nanotube transistors.

### **Publications or notable interactions:**

C.H.L. Quay, John Cumings, S.J. Gamble, A. Yazdani, R. de Picciotto, H. Kataura, and D. G.-G., “Transport properties of carbon nanotube C<sub>60</sub> peapods”, *Phys. Rev. B* **76**, 073404/1–5 (2007).

C.H.L. Quay, John Cumings, Sara Gamble, R. de Picciotto, H. Kataura, and D. G.-G., “Magnetic field dependence of the spin-1/2 and spin-1 Kondo effects in a quantum dot”, *Phys. Rev. B*, 245311/1–5 (2007).

J.A. Sulpizio, Z.Z. Bandic, and D. Goldhaber-Gordon, “Nanofabrication of top-gated carbon nanotube-based transistors: Probing electron-electron interactions in one-dimensional systems”, *Journal of Mat. Res.* 21 2916-21 (2006).

T. Brintlinger, Yi Qi, K.H. Baloch, D. G.-G., and John Cumings, “Electron Thermal Microscopy”, *Nano Letters* 8, 582 (2008).

### **New discoveries since Sep 2007 progress report:**

Quantum dot behavior in electron flow through graphene nanoribbons (in collaboration with Hongjie Dai, Stanford Chemistry).

### **Honors/Awards:**

2002 AFOSR Presidential Early Career Award in Science and Engineering (PECASE) (*actually awarded 2004*). Awarded to two early-career scientists or engineers per year.

2004 David and Lucille Packard Fellow. 16 awarded nationwide to early-career faculty across all fields of science and engineering.

2003 Alfred P. Sloan Foundation Fellowship

2004 Research Corporation Research Innovation Award

2004 Named Co-Director (with Kam Moler) of NSF-Stanford-IBM Nanoscale Science and Engineering Center: “Center for Probing the Nanoscale”

2006 National Academy of Sciences Award for Initiatives in Research

2007 Hellman Faculty Scholar